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Experimental Verification of Board Level Shielding Variability at Microwave Frequencies

Andy Marvin
Department of Electronic Engineering
University of York
York, UK
andy.marvin@york.ac.uk

John Dawson
Department of Electronic Engineering
University of York
York, UK
john.dawson@york.ac.uk

Martin Robinson
Department of Electronic Engineering
University of York
York, UK
martin.robinson@york.ac.uk

***Abstract*—This paper shows that the Shielding Effectiveness of a printed circuit board shield (PCBS) varies depending on the shield's external environment when the circuit board level shield is installed within a larger external enclosure. A reverberation chamber based technique is demonstrated that allows the underlying Shielding Effectiveness of the circuit board level shield to be evaluated along with an estimate of its expected variability due to the external enclosure.**

***Keywords*—shielding effectiveness, reverberation chamber, printed circuit board shield**

I. Introduction

The work described in this paper has been undertaken as part of the IEEE Project P2716 "Guide for the Characterization of the Effectiveness of Printed Circuit Board Level Shielding" [1]. Before this project there has been a number of papers published addressing this subject. In [2] our earlier work on near-field shielding measurement of Printed Circuit Board Shields (PCBS) in a reverberation chamber is described. Reference [3] describes an alternative stripline technique for the measurements. Various proposed techniques are reviewed in [4] which eventually led to the IEEE P2716 project. PCBSs differ from other shielding enclosures in a number of ways. PCBSs are typically small with linear dimensions of a few millimetres or tens of millimetres. Usually they only have five rather than six sides, the sixth side being the ground plane of the printed circuit board. Connection to the circuit board is usually by multiple solder points on the shield or on an open shield frame over which a shield is clipped. This type of structure results in numerous small apertures and slots in the shield and the shielding performance is modest, particularly at microwave frequencies. The shielding performance also depends to some extent on the quality of the installation.

In [5] we showed that the shielding performance of a PCBS is variable if the shielding is measured inside a reverberation chamber. The shielding performance of the PCBS was shown to be dependent on the position of the mechanical stirrer within the chamber. Variations with a range of +/- 20dB of the mean were observed. The rationale for this type of measurement is that a PCBS is likely to be installed on a circuit board which is housed inside a larger shielded equipment enclosure. At microwave frequencies the outer enclosure is likely to be resonant or reverberant and the circuit board shield is likely to be resonant. Thus the exact electromagnetic environment of the PCBS is unknown. The reverberation chamber is able to replicate this variability. The PCBS is usually deployed to shield its contents from interference sources or victims in its immediate vicinity, probably located on the same circuit board. The shielding measurement should reflect this.

In this paper we extend the work presented in [5] to show that the reverberation chamber measurements indicate a valid way of examining the variability of the shielding performance exhibited by a PCBS deployed in different external environments.

All the data presented below pertain to a single PCBS which remained installed on the measurement jig (Fig. 1), as shown in Fig. 2, throughout the measurement campaign. This was to avoid repeatability problems associated with shield installation and removal. In practice a PCBS would only be installed once during production. The frequency range illustrated in all cases is between 5GHz and 20GHz.

In II the shielding performance of the PCBS is measured in a number of different external environments illustrating the effect of the external environment on the shielding performance. In III the PCBS shielding performance is measured in the reverberation chamber using the techniques described in [5]. Comparison of the two measurement sets is made in IV illustrating the utility of the reverberation chamber measurements for assessing the variability of the PCBS shielding performance.

II. Board Level Shielding Measurements

There are several definitions of the Shielding Effectiveness (SE) of enclosures. The most common are found in IEEE Std 299.1 [6]. The SE is defined either in terms of the ratio of incident external electric field strength to the internal electric field strength or in terms of the incident electromagnetic power density to the electromagnetic power density inside the enclosure. Both are acceptable in the microwave frequency range. In either case, a means of measuring the internal field strength or power density is required. For this work, the predominant shielding issue is concerned with external sources or victims being in the vicinity of the PCBS. The PCBS is also likely to have internal contents that occupy a significant fraction of its internal volume and that have energy absorbing properties. The approach taken in this work is to make measurements based on the power coupled into the PCBS contents with and without the PCBS present.

In order to measure the shielding effect of a PCBS a measurement jig has been designed. This comprises a printed circuit card with a continuous ground plane on each side with dimensions of 140 mm x 220 mm. The internal contents of the PCBS are represented by a 25 mm long 50 Ω characteristic impedance stripline terminated at each end with matched loads, one of which is the measurement instrument, here a Vector Network Analyser (VNA).

Fig. 1. Striplines (length 25 mm) mounted on the measurement jig.

Identical striplines are mounted external to the PCBS on the groundplane as shown in Fig. 1. The striplines are marked as S (shielded, inside the PCBS), P (parallel to S), and O (orthogonal to S). The O and P striplines are 50 mm from the centre of the S stripline. Fig. 2 shows the jig with the PCBS installed over the S stripline. The PCBS has dimensions of 38 mm x 50 mm x 4 mm. Fig. 3 shows the parallel (P) stripline close up. The original jig described in [5] had air-spaced striplines. These proved fragile and unreliable. The current jig uses dielectric-spaced striplines soldered at each end to the extended centre conductors of the SMA female jacks on the underside of the jig.

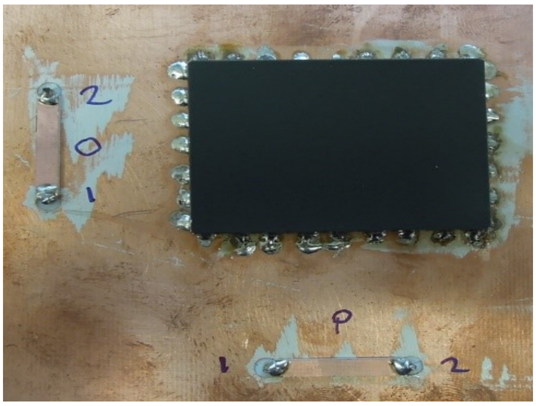

Fig. 2. PCBS (size 38 mm x 50 mm) installed on the measurement jig.

The dielectric of the SMA jack extends to the top surface of the jig through a plated hole. This structure prevents energy coupling into the striplines through the dielectric substrate between the groundplanes of the jig.

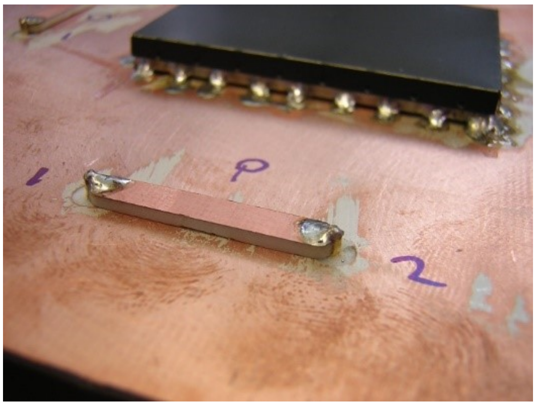

Fig. 3. Close up of the parallel stripline, with part of the PCBS behind.

The SE of the PCBS is measured by taking the ratio of the power coupled between one of the external striplines (O or P) and the internal stripline (S) with and without the PCBS installed. If a VNA is used to perform the measurement, the *SE* expressed as a ratio in decibels can be written in terms of the measured S parameters, as in (1). Here S_{21s} and S_{21u} are the measured S parameters shielded and unshielded.

$$SE = 10log_{10}\frac{|S_{21u}|^2}{|S_{21s}|^2}\ dB \tag{1}$$

If the PCBS is installed on a circuit board located inside an outer enclosure, then the coupling between the striplines has two components: the direct coupling between the two striplines with and without the shield present, and the indirect coupling between the striplines caused by reflections from the outer enclosure walls and other outer enclosure contents. The outer enclosure affects the measured SE in two linked ways. The first is the unknown indirect coupling due to the wall and other reflections. The second is the difference in the outer enclosure's resonant or reverberant behaviour, caused by the enclosure dimension changes associated with the installation of the PCBS. This latter effect is unavoidable in any SE measurement performed in a resonant or reverberant environment.

As well as the shielding measurements, the Q factors of the outer enclosures with the PCBS installed were estimated using the frequency response autocorrelation technique described in [7]. The Q factors vary with frequency. For measurement comparison we quote estimated values of Q factor at 15GHz (actually obtained over 14.5 to 15.5 GHz).

All the following results presented below were taken with a measurement bandwidth of 1kHz, a VNA output power of 10dBm and a 1MHz frequency step. All were taken with the VNA connected to ports S1 and P1 on the measurement jig and thus represent the SE of the PCBS for the parallel stripline case. The frequency range presented is from 5GHz to 20GHz.

Fig. 4 shows a measurement of the SE of a PCBS installed inside an outer enclosure of dimensions 50 mm x 110 mm x 180 mm, according to (1). The results show the 1 MHz frequency resolution. Also shown is a 50 MHz wide moving average plot of the same data. Fig. 4 shows that there is substantial variability in the 1MHz resolution data, showing the influence of the indirect coupling. The moving average plot shows the underlying SE structure of the PCBS. This will be illustrated further below and in IV.

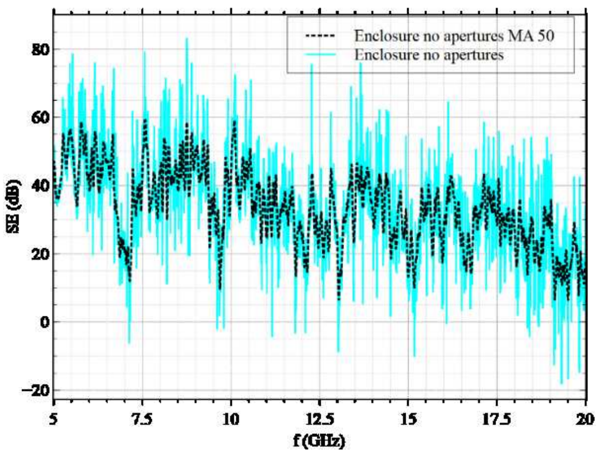

Fig. 4. SE of PCBS mounted in the 50 mm x 110 mm x 180mm enclosure.

The measurement jig with the enclosure attached is shown in Fig. 5. The measurement jig forms one side of the external enclosure. The SMA connectors to the three striplines can be seen. Four of them have a matched load on. The S1 and P1 ports without loads were connected to the VNA for the measurements, so were also terminated in 50 Ω. From Fig. 5 and Fig. 7 below, it can be seen that there is a number of slots in the external enclosure, seven in all on three faces.

The data in Fig. 4 are for the case where all the slots were covered with adhesive copper tape giving an outer enclosure with no apertures. The average Q factor of the enclosure resonances is 1400 at 15GHz. Fig. 6 shows the SE and the moving average (MA) data when the apertures are uncovered and a block of Eccosorb LS22 carbon-loaded polyurethane foam absorber installed as shown Fig. 7. In this case the apertures and absorber reduce the average Q-factor of the enclosure resonances to 250 at 15GHz, resulting in a reduced variability about the moving average compared with Fig. 4.

Fig. 5. Outer enclosure (above) installed on the measurement jig.

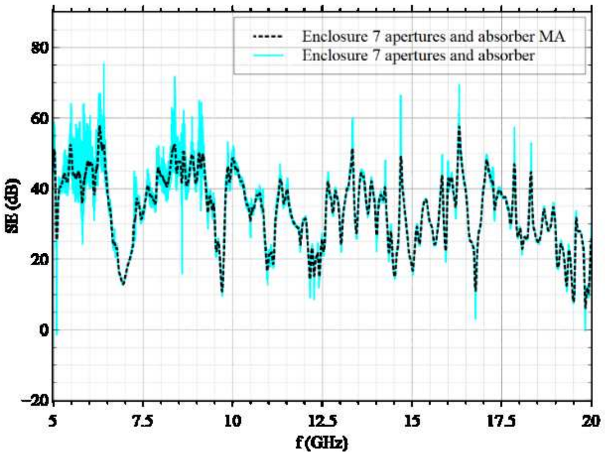

Fig. 6. . SE of the PCBS mounted in the 50 mm x 110 mm x 180 mm enclosure with apertures and absorber.

Also visible in Fig. 7 are two probe monopoles installed on the lower and right hand walls of the enclosure. These were used to measure outer enclosure frequency responses needed for the Q factor estimates.

Fig. 8 shows the measurement jig installed in a larger enclosure with dimensions 170 mm x 400 mm x 460 mm with the enclosure cover removed.

Fig. 9 shows the measured SE with a 1 MHz frequency resolution and the 50 MHz wide moving average. Again, substantial variability is evident, with the underlying shielding performance of the PCBS apparent from the moving average plot.

The average Q factor of the enclosure resonances is 4700 at 15GHz, this higher value being expected due to the larger volume of this enclosure.

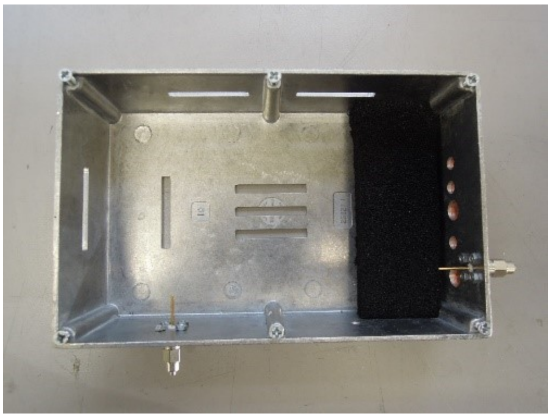

Fig. 7. Enclosure showing 7 apertures and absorber (to right).

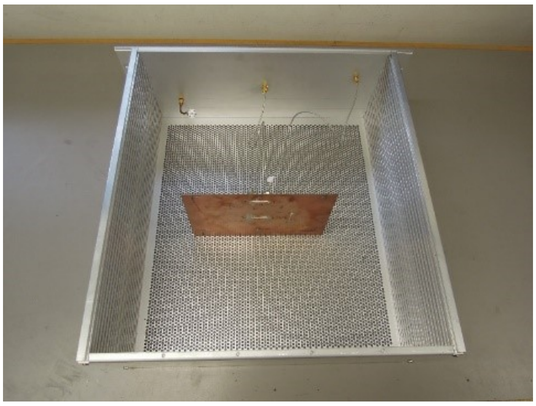

Fig. 8. Jig installed in the 170 mm x 400 mm x 460 mm enclosure.

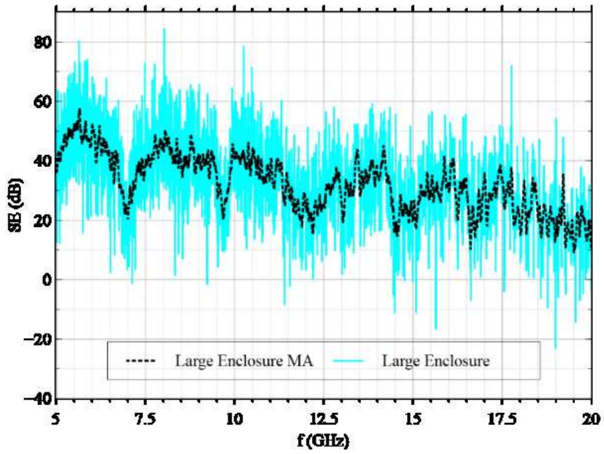

Fig. 9. SE of PCBS in 170 mm x 400 mm x 460 mm enclosure.

III. REVERBERATION CHAMBER MEASUREMENTS OF PCBS.

In II it was demonstrated that the measured SE of a PCBS is dependent on its external environment after installation. Such measurements are unlikely to be practicable and the measurement of the SE requires a technique that not only gives the underlying SE of the PCBS, but one that also indicates its variability in differing external environments with variable levels of resonance or reverberation. In [5] we proposed three SE metrics, the Unstirred SE, the Stirred SE and the Point SE. All three are measured in a reverberation chamber. In this paper the Unstirred SE and the Point SE are considered further.

The Unstirred SE (SE_{us}) is measured by taking the ratio of the phasor average S parameters, denoted by < > in (2), over a complete stirrer rotation in the reverberation chamber. Taking the phasor average removes the variability due to the stirring process and gives an estimate of the direct coupling between the internal and external striplines. It is equivalent to a measurement of the SE in an anechoic environment where only direct coupling exists:

$$SE_{us} = 10\log_{10}\left(\left|\frac{\langle S_{21u}\rangle}{\langle S_{21s}\rangle}\right|\right)^2 \text{dB} \quad (2)$$

The Point SE (SE_n) is a measure of the SE of the PCBS at each stirrer position. The multiple stirrer positions are surrogates for the range of external environments in which the PCBS may be deployed. For n stirrer positions, a population of n SE measurements at each frequency is obtained as :

$$SE_n = 10\log_{10}\left|\frac{S_{21u(n)}}{S_{21s(n)}}\right|^2 \text{dB} \quad (3)$$

$$SE_{point(mean\ dB)} = \langle 10\, log_{10}\left|\frac{S_{21u}(n)}{S_{21s}(n)}\right|^2\rangle \text{ dB} \quad (4)$$

The Point SE enables the examination of the range of variability to be expected in a PCBS SE measurement. In [5] it was shown that the Point SE follows a log-normal distribution and thus the Point SE mean expressed in dB follows a normal distribution. The +/- 3std (three standard deviations) curves (Fig. 10) show the limits of the variability to be expected in more than 99% of cases.

For the reverberation chamber measurements the stirrer was rotated through a single turn with 100 stirrer positions. The chamber has dimensions 4.7 m x 3.0 m x 2.37 m and has a Q factor of 10^5 at 15GHz.

IV. Comparison of Reverberation Chamber Measurements with External Enclosure Measurements.

The data shown in Fig. 10 are for the same PCBS used in the measurements in II. The Mean Point SE measurements closely follow the Unstirred SE measurement.

In Fig. 11 the comparison between the moving average SE measurements in the smaller external enclosure with and without apertures and absorber and the larger external enclosure is shown. The underlying SE of the PCBS is clearly apparent although external environment differences still exist.

Fig. 12 shows the comparison of the Mean Point SE measurement from the reverberation chamber with the moving average SE for the smaller external enclosure with apertures and absorber.

The underlying similarity between the two measurements is evident indicating that the Mean Point dB SE is a useful measure of the average performance to be expected of a PCBS installed in an external enclosure. In addition the statistics of

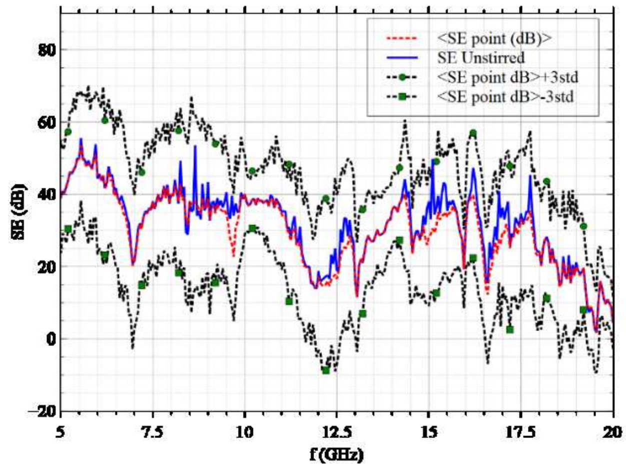

Fig. 10. . Unstirred SE and Mean Point SE with three standard deviations.

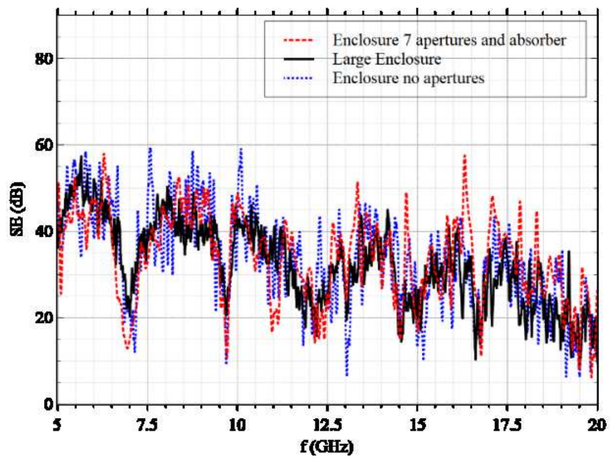

Fig. 11. Comparison of Moving Average SE measurements in the two external enclosures.

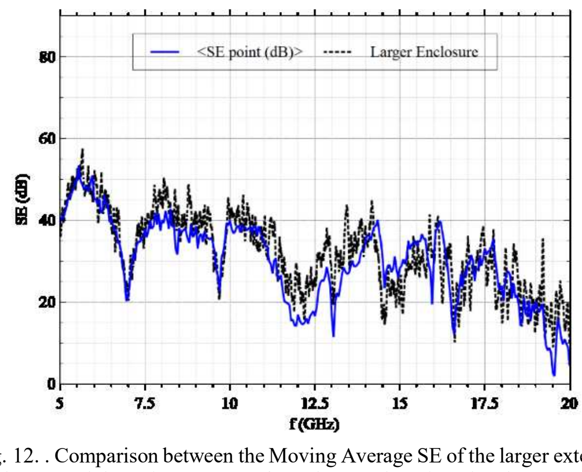

Fig. 12. . Comparison between the Moving Average SE of the larger external enclosure and the Point Mean SE from the reverberation chamber.

the Point SE can be used to indicate the possible variation in SE that the installed PCBS may exhibit. Fig. 13, Fig. 14, and Fig. 15 show the three standard deviation bounds of the Point SE along with the moving average of the SE of the PCBS installed in the smaller external enclosure with no apertures or absorber, the smaller external enclosure with absorber and apertures and the larger external enclosure. In each of these cases the moving average SE is almost entirely contained within the three standard deviation bounds of the Point SE statistics.

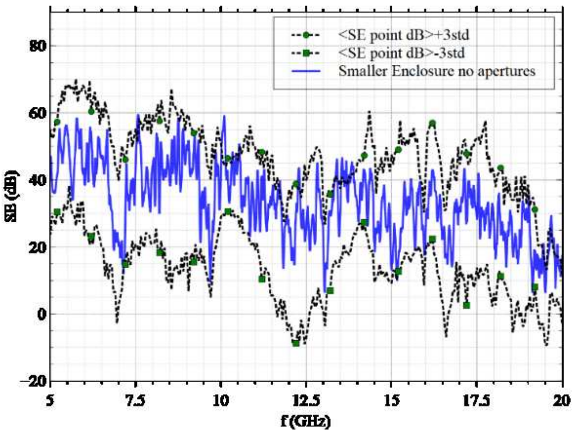

Fig. 13. Smaller external enclosure with no apertures SE and Point SE bounds

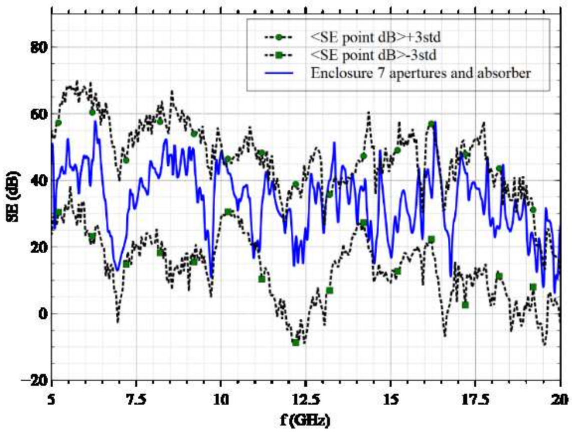

Fig. 14. Smaller external enclosure with apertures and absorber and Point SE bounds.

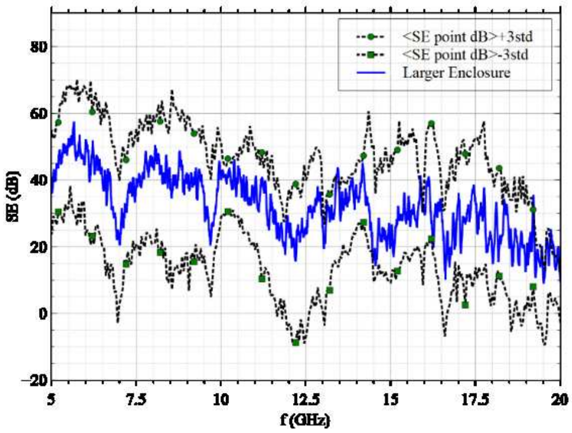

Fig. 15. Larger external enclosure SE and Point SE bounds.

V. Discussion

By examining the SE of a PCBS in a number of external enclosures, we have demonstrated that the shielding effectiveness of a PCBS installed on a circuit board inside a larger external enclosure is dependent on the properties of the external enclosure in the microwave frequency range. The variability of SE is due to the variability of the properties of the external enclosure, which are determined by its size, shape, and the absorption properties of the external enclosure's contents, walls and apertures. The energy coupled through the shield has two components, the directly coupled energy and the energy scattered by the external shield walls and contents. The external enclosure properties determine the scattered energy coupled through the shield. Without sophisticated numerical modelling, this scattered energy coupling is not predictable.

When the SE of the PCBS is measured *in situ* in an external enclosure, some of the variability measured is due to the change in the geometry of the interior of the external enclosure when the PCBS is installed, affecting the scattered energy coupling. Thus measuring the SE of a PCBS in situ in an external enclosure only gives an estimate of the PCBS SE in that one particular installation. Such a measurement could only be performed when all other aspects of the equipment design are finalised. Even then it is unlikely that an SE measurement would be possible. Only the acceptability or unacceptability of the particular PCBS in the specific application could be established.

The Point SE metric, described in [5], enables the measurement of the PCBS SE in a reverberation chamber. The mechanical stirring process in the reverberation chamber mimics the variability of the range of possible external environments in which the PCBS could be installed. The Point SE metric gives a population of SE values representing this range of external environments. The statistics of the Point SE metric performed on a PCBS are an indicator of the level of variability that can be expected in the SE of the PCBS when it is installed for use. Measurements of the SE of a PCBS made in an external enclosure exhibit rapid frequency-dependent variability, due to the resonant or reverberant effects mentioned above. The underlying PCBS SE can be observed by frequency-averaging this data. The Point SE is a metric that examines the PCBS SE at each frequency over a range of external environments. The mean of the Point SE data is shown to follow the Unstirred SE of the PCBS itself, equivalent to an anechoic measurement of the PCBS SE. The PCBS SE measured in a range of external enclosures has been shown to lie within the variability of the Point SE data, thus demonstrating that the Point SE metric is a potentially useful metric of the utility of a PCBS.

Finally, it was anticipated that external enclosures with lower Q factors would exhibit a lower level of variability. Comparison of Fig. 4 and Fig. 6 shows that whilst the variability around the moving average is lower for the smaller external enclosure with the lower Q factor, the magnitude of the variability of the moving average is similar. In the case of the larger enclosure with the highest Q factor the moving average result is closest to the Point Mean SE. This remains under investigation.

VI. Conclusion

In this paper we have shown that the SE of a PCBS is dependent on its installation in a larger external enclosure. The size of the external enclosure, the presence of apertures and other dissipative internal contents all effect the SE of the installed PCBS. Measurement of the installed SE of a PCBS is usually impractical. Using the reverberation chamber based SE metrics described in [5] allows the PCBS SE and the likely extent of its installation dependent variability to be assessed prior to installation.

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